

The Transpiration of Emerged Water Plants: Its Measurement and Its Relationships

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BY

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THE
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THE TRANSPIRATION OF EMERSED WATER PLANTS:
ITS MEASUREMENT AND ITS RELATIONSHIPS¹

CHARLES HERBERT OTIS

(WITH THREE FIGURES AND FOURTEEN CHARTS)

Introduction

The evaporation taking place from free water surfaces has been the subject of much experimentation during the past century, and the laws governing this phenomenon have been quite definitely stated. The matter of transpiration of plants, a special kind of water evaporation, has also been the subject of a great deal of theoretical and experimental investigation, and we know the quantity of water transpired by certain plants in various situations and some of the factors which influence it. But, although the subject is of great importance in regions of small rainfall and scant water supply, especially where immense irrigation and water supply projects are involved, practically no investigation of any importance has been conducted to determine the effect of emersed water plants on the evaporation from a water surface.

It has been a matter of common belief that emersed water plants transpire large amounts of water, although there seems to be little evidence in support of such belief. FANNING (6) says, "Marshy margins of ponds are profligate dispensers of vapor to the atmosphere, usually exceeding in this respect the water surfaces themselves." Such statements as this, unsupported by experimental

¹ Contribution no. 143 from the Botanical Department of the University of Michigan.

evidence, are of only passing interest, yet they constitute all of the scanty literature on the subject.

This investigation was undertaken to secure experimental data leading to a better knowledge of the quantity of water transpired by emerged water plants, its relationships, and some of the factors which influence it.

Relation between the amount of water transpired and the amount of water absorbed by the roots

WOODWARD (13) in the latter part of the seventeenth century measured the amount of water absorbed by the roots, and considered this amount to be a measure of the quantity transpired. BESSEY and WOODS (1), in criticism of this method, pointed out that such observations are misleading, that the amount of water absorbed is not necessarily proportional to the amount transpired. Two years later, criticizing a similar mode of reasoning by SCHNEIDER (10), WOODS (12) says, "first of all he has made a very great mistake in assuming that the amount of water absorbed by the roots of a plant represents the amount transpired," and quotes in support of his argument the investigations of EBERDT, BURGERSTEIN, VINES, and GOODALE. WOODS also points out that "transpiration is not something which protoplasm *does* but something which it *resists*. It is not a physiological function or activity of protoplasm, although it may have a physiological relation to the normal development of certain plants or parts of plants. Transpiration is nothing more than evaporation."

BURGERSTEIN (2) reports that VESQUE, using a 0.35 per cent nutritive solution in which bean plants were grown for a period of 56 days, found a water intake of 92.65 gm. and a water outgo of 82.105 gm. He cites also the work of KRÖBER with leafy branches of *Asclepias incarnata*, and shows by the results given in table I that the amount of water taken up by the cut surfaces differs from the amount given off by transpiration.

EWART and REES (5), working with trees, make the statement that "The rate of evaporation per sq. m. of leaf surface from cut branches, whether placed in water or not, is always less than from a plant rooted in the soil, under otherwise similar conditions."

Other recent investigators, among them CLEMENTS (4) and GATES (7), have come to the same conclusion. KRÖBER's results may be criticized, then, on the basis that cut stems and not naturally growing plants were used. It is to be noted, however, that, during the period of the experiment, the amount of water absorbed and the

TABLE I

	Absorption	Transpiration	cc.
9:15 A.M.—6:25 P.M.	11.30	12.80	+1.5
6:25 P.M.—9:50 A.M.	8.05	6.48	-1.57
9:50 A.M.—7:05 P.M.	11.30	11.80	+0.5
7:05 P.M.—7:25 A.M.	7.67	5.21	-2.46

amount transpired were not greatly different, being 38.32 cc. in the one and 36.29 cc. in the other, showing a difference of 2.03 cc. for 42 hours. EBERDT's results with *Helianthus annuus*, as reported by BURGERSTEIN, show even a smaller difference, his figures for a period of 24 hours being as given in table II.

TABLE II

Time	Evaporation of water in cc.	Absorption of water in gm.
7:15 P.M.—8:45 A.M.	16.67	15.55
8:45 A.M.—11:45 A.M.	4.95	5.53
11:45 A.M.—3:00 P.M.	5.50	7.40
3:00 P.M.—7:15 P.M.	6.45	5.50
7:15 P.M.—7:15 P.M.	33.57	33.98

EBERDT's results, employing the potometer method, are not entirely satisfactory for the reasons stated above. Summarizing the results of these investigations, however, BURGERSTEIN states that if experiments are conducted for periods of 24 hours or longer, using plants that are healthy and under normal conditions for growth and transpiration, and only approximate values are desired, there may be assumed a certain proportionality between water intake and water outgo.

VESQUE (11), experimenting with whole plants subjected to varying physical conditions, comes to the conclusions (1) that the

two functions, absorption and transpiration, are not necessarily proportional; (2) that the absorption is equal to the transpiration when the plant is growing under average and fairly constant conditions, as in diffuse light and in average humidity; (3) that when a plant growing under normal conditions is placed in a dry atmosphere, transpiration is greater than absorption; (4) that when a plant growing under normal conditions is exposed to a saturated atmosphere, the absorption, in obedience to the vacuum already existing, is greater than the transpiration; and (5) that when a plant lacks water, the suction produced by transpiration is not lost, but it accumulates to act immediately when the roots come in contact with water, when absorption is much more energetic than transpiration.

CLEMENTS (4) experimented with potted plants of *Helianthus annuus* and found by careful weighing of the amount of water absorbed by the roots and the amount transpired by the stem and leaves that at the end of 5 days the one equaled the other. His results were as shown in table III.

TABLE III

	Wt. of pot and dry soil	Wt. of pot and wet soil		Total H ₂ O	H ₂ O left	H ₂ O absorbed	H ₂ O transpired
		I	II				
I. . . .	1846.0 gm.	2218.0 gm.	2174.3 gm.	372.0 gm.	328.3 gm.	43.7 gm.	43.7 gm.
II. . . .	1886.7 gm.	2253.2 gm.	2221.6 gm.	366.5 gm.	334.9 gm.	31.6 gm.	31.6 gm.

To sum up the conclusions of these investigators, the results indicate for land plants growing under natural conditions:

1. That there may be slight discrepancies between the amounts absorbed and transpired if the periods between measurements are separated by a few hours only.

2. That for a longer interval of time between measurements the amount transpired is essentially equal to the amount absorbed.

Hence the amount of water absorbed may be taken as a measure of the amount of water transpired, certainly in view of the fact that any slight error can be scarcely larger than that of any other method applicable to the field. One such error which is known to exist, but which is insignificant when one is dealing with relatively

short periods of time, is the small amount of absorbed water which is used in the building up of plant tissue and also that which becomes a part of the cell sap. Further, since the roots of emersed water plants are constantly in contact with saturated soil, no matter what the transpiration demands, they are never temporarily deprived of water, as may be the case with land plants during periods of excessive transpiration; nor are water plants ordinarily subjected to as great extremes of temperature, relative humidity, and other external factors as are land plants. It is to be concluded, then, that the relations between absorption and transpiration stated above will hold equally well for even short intervals of time, as for 3-4 hours. In the experiments which follow, however, longer periods than this have been chosen, usually of about 12 hours.

Apparatus²

The apparatus which was finally adopted consisted essentially of nine large tanks supported in the water by two pontoons. Each tank was equipped with a simple device for measuring the evaporation from the tank. A recording thermometer was housed in a small shelter about 2 m. from the pontoons. Relative humidity was ascertained by means of a cog or "egg-beater" psychrometer (4), which was in each case rested on a support about midway of the vertical height of the growing plants. A barometer of the United States Weather Bureau pattern, but graduated in the metric system, was maintained on shore and read at intervals for the air pressure. Centigrade thermometers for ascertaining the temperature of the water both within and outside the tanks, and graduates of various capacities for measuring the amount of water evaporated were employed. In the experiments conducted on the Huron River at Ann Arbor, a Green's recording anemometer making electrical contact every tenth mile was employed in addition to the apparatus just mentioned. The cups of the anemometer revolved in a plane about 5 dm. above the surface of the water.

² An excellent summary describing instruments adapted to the measurement of evaporation from water surfaces is contained in C. F. MARVIN's *Methods and apparatus for the study of evaporation*. II. Instruments (9).

The tanks, which were specially constructed for the experiments, were 76 cm. in diameter and 81 cm. in depth, inside measurements (fig. 1). Both cylinder and bottom were constructed of heavy galvanized iron, all joints being well riveted and soldered. A heavy iron band was riveted to the rim, through which were bored four holes, allowing the tank to be supported by spikes driven into the framework of the pontoons. Lighter iron bands

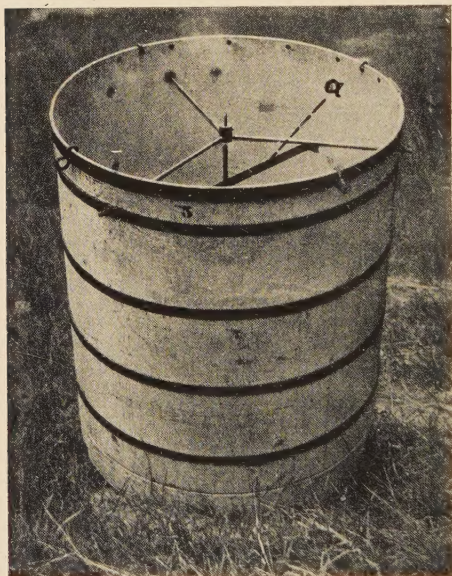


FIG. 1

were riveted internal iron braces, one of which is shown at *a*, fig. 1. The lower edge of the tanks projected about 10 cm. below the bottom. Pieces of wood 5 cm. by 10 cm. in cross-section were fitted into this space and spiked to the projecting sides, as shown in fig. 2. This construction made a tank of great stiffness, which was not easily deformed by rough handling or the tilting caused by wave action, and which produced a solid surface to which the measuring device was secured.

The foregoing features were essential, since any deformation of the tank during the progress of the experiments would cause a corresponding change in the volume of the tank and a similar error in the reading.

The measuring device was a modification of the well known Hooke gauge, and was unique in its simplicity and in the accuracy with which readings could be made. A brass tube of about 6 mm. inside diameter was supported vertically in the center of the tank. The lower end of the tube was threaded and screwed into a socket which was riveted and soldered to the bottom of the tank, while

the upper end terminated in a heavy brass collar. This collar was provided with a socket into which was slipped a solid brass rod, or point, pointed at its upper end. The points were first turned up in a lathe, after which they were placed in a form and ground on an oil stone until a microscopical test showed them all to be of the same angle and of a uniform degree of sharpness. The angle of the cone thus formed was 45° , which was found experimentally to give the best results. Screwed into the sides of the collar at angles of 120° with each other were three iron radius rods terminating in



FIG. 2

the heavy iron band at the rim. The outer extremity of the rods was threaded for a considerable distance, so that by means of lock-nuts and rubber gaskets on either side of the heavy band the point could be centered with ease and accuracy. It was essential that the point should be in the exact center of the tank, since only in this position could accurate readings be made in case the tank were tilted slightly from the vertical. The points in all the tanks were set at a distance of 4.5 cm. below the level of the rim.

The pontoons which supported the tanks in the water were at first constructed of rough hemlock lumber and covered with a good grade of asphalt roofing felt. They consisted of two boxes

4.26 m. long, 3 dm. wide, and 3.5 dm. deep. The boxes were left open on the upper side for a greater part of their length to allow a ballast of rocks to be placed to sink the tanks to the required depth. Any water which might enter the pontoons could also be removed through the same opening. It was found to be an advantage to have these pontoons extra large in order that the work of filling the tanks with soil and the placing of plants might be done from the pontoons rather than from a less stable boat. Cross-timbers 5 cm. by 10 cm. in cross-section held the pontoons rigidly

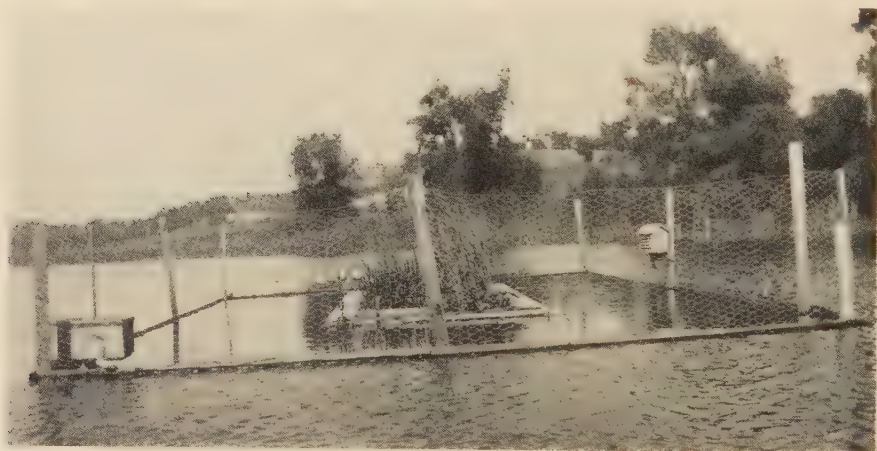


FIG. 3

in place and provided a support for the tanks. It was found necessary to place poultry netting of 5 cm. mesh around the finished raft to a height of 3 dm., and in the horizontal-spaces between the tanks, to exclude the turtles which infested the water at this place and which proved rather troublesome. These first pontoons proved to be too frail, since they were easily damaged, with consequent submersion of the entire apparatus. They were replaced the following year by more substantial pontoons with solid tops. The interior of these was subdivided by four water-tight partitions into five compartments. Through holes in the top provided with corks water could be placed in or taken from the compartments, and it was by this means that the proper level of the tanks was

maintained. The wire netting was also removed from the raft, and a netting 1.5 m. high was substituted at a distance of 1.5-2 m. from, but inclosing, the raft, since turtles were not abundant. The relations of the various instruments and the pontoons is shown in fig. 3.

Methods

Readings were regularly made early in the morning and late in the afternoon or early evening, since at these times the water was usually quite still and the light conditions best for accurate readings. A boat was necessary at all times, all work being done from it as soon as observations were begun. Measurements made at the station included wet and dry bulb temperatures as indicated by the psychrometer. Temperatures of the water in the tanks and of the water surrounding the tanks were ascertained and recorded both at the surface and at a depth of 76 cm. beneath the surface. Continuous records of air temperature and wind were made by the recording instruments. The amount of water taken up by the plants or evaporated from the water surface was ascertained by measuring the quantities of water it was necessary to place in the tanks to bring the water to the standard level, as indicated by the height of the point of the brass rod. Water taken from the lake or river surface adjacent to the tanks was always used, since it was of the same temperature and had other characteristics in common with the water in the tanks. Once a week the tanks were filled to overflowing with several bucketfuls of water rapidly applied to remove any scum or refuse matter which might accumulate and which would influence the evaporation therefrom.

The best way to ascertain accurately the amount of water to be added to a tank in each case was found to consist in adding a little more water than was necessary to cover the point. On placing the eye close to the level of the water a point could be found where the entire surface of the water in the tank appeared like a bright mirror. Then, with the eye directed toward the center of the surface, a small quantity of water was removed. As soon as the surface became still, an examination was made for the appearance of the point. If it did not show, more water was removed, until finally a minute black spot was distinguishable in the center of the

mirrored surface. (If, at this stage, more water is removed, the minute spot rapidly enlarges, spreading out in a circle around the exposed point.) A very small quantity of water was then added, just enough to obliterate entirely the dark spot. Usually the finger was applied to the point at this stage, a slight rubbing serving to clean the point and to break the surface film of the water over the point. The point was shown to be just beneath the surface, as, on lightly touching the water with the finger, a tiny wave would be sent across the surface, and the point would appear momentarily to be immediately obliterated. This phenomenon was most readily observed when the light was somewhat diminished. At midday the sun on a cloudless day was so intense that the eye was flooded with the light reflected from the water surface, making it difficult to see the dark spot. Repeated observations under varying conditions carried out with a test tank showed that on the average a change in water height produced by the addition or subtraction of 25 cc. of water could be detected. Since the area of water surface in the tank approximated 4,575 sq. cm., this volume would give a theoretical difference in height, or minimum error due to observation, of 0.05 mm.

Experiments

Experimental stations were established and maintained during the summers of 1910 and 1911. The first was located in a bay of about 12 hectares' extent in Portage Lake, situated 27 km. northwest of Ann Arbor, Michigan. A long, narrow peninsula covered with a scrubby growth of trees and shrubs separated the bay from the lake proper and protected the station from the prevailing westerly winds. It was subsequently found necessary to establish a boom of floating logs on the south and east as a protection against occasional winds from these directions.

Two tanks at the diagonal corners of the raft contained neither soil nor plants and were used to ascertain the evaporation from the free water surface. The other tanks were supplied with lake mud, the depth depending upon the plants placed therein. Plants from the immediate vicinity were planted in these tanks, the depth of the water being in all cases identical with the depth of the water where the plants were naturally growing. Care was also taken to set the

plants as nearly as possible in the same density of stand as naturally growing plants in the lake. Where there was any tendency for the plants to work their way out of the soil, which was of common occurrence among the larger kinds, on account of their natural buoyancy and the extreme looseness of the newly placed soil, stones were used freely to press down the roots and hold them in place. The plants used during 1910 were *Scirpus validus* and *S. americanus*, *Sagittaria latifolia*, *Castalia odorata*, *Pontederia cordata*, *Typha latifolia*, *Zizania aquatica*, and *Eichhornia speciosa*. The two latter were discontinued before the measurements were begun, as the *Zizania* was twice completely destroyed by water animals and the *Eichhornia* floated away the first time the raft sank. The plants, after transplanting, were allowed to remain undisturbed for a period of two weeks, during which time they became well established.

At the beginning of the experiment measurements were made of the area of leaf and stem surfaces exposed to the action of the air. These measurements were made in the following manner. In the case of those species having petioles and expanded blades (as *Sagittaria* and *Pontederia*), a tracing was made of every leaf blade or portion of a leaf blade above the standard water level, and the upper and lower diameters and length of the petioles above water were recorded separately. Subsequently the area of blade surface was ascertained by use of a planimeter and the area of petiole surface was calculated as the area of the frustum of a cone. In the case of *Scirpus validus* the height of the culm above the water and its basal diameter were recorded, its surface being calculated as the surface of a cone having the dimensions recorded. With *Scirpus americanus* similar measurements were made, the surface being treated as the surface of a pyramid whose base is an equilateral triangle. The leaves of *Typha* were measured for the length exposed to the air (not the height above the water) and the width of the corresponding base, the surface exposed being calculated by treating each leaf as a triangle whose base is the width and whose altitude is the length given. Finally, a photograph of the surface of the tank containing *Castalia* was made from a point exactly above the center of the tank, since leaf tracings of the

floating leaves could not be made without injuring them. By means of the planimeter and a simple proportion the surface of the leaves exposed was approximated. During the course of the experiment, when leaves or parts of plants were for any reason removed, the parts were measured and a record was made of the date of removal. At the end of the experimental period all parts above water were again measured and calculated in the same manner as outlined above. In making calculations the slide rule was resorted to wherever practicable.

A second station was established in the summer of 1911 in the Huron River near Ann Arbor. The river at this place is about 60 m. wide. There is little or no natural protection on any side, and it was necessary to inclose the entire station by a stationary boom. The plants were in this case taken from the river near by. They included *Scirpus validus*, *Typha latifolia*, *Castalia odorata*, and *Pontederia cordata* used the first year, together with *Sparganium eurycarpum* and *Acorus Calamus*. Owing to the withdrawal of the water for a period of several weeks, while repairs were being made on a near-by dam, the *Sagittaria latifolia* was all but destroyed and could not be used. Consequently only eight tanks were used. Two tanks were used as controls and the preliminary treatment of the plants was the same as at the Portage Lake station. The plants were not measured, however, and the surface area exposed to the air was not ascertained.

Just before measuring observations were begun, pontoons and tanks were sunk to such a depth that the water in the tanks and the water of the lake were in the same horizontal plane, which was 4.5 cm. below the level of the rim.

Ecological and physiological aspects of plants used

1. *Scirpus validus* Vahl. (great bulrush) inhabits the still water at the margins of lakes, ponds, and quiet streams, or covers shallow shoals in lakes, often forming thick stands of large extent. The maximum depth of water in which good growth occurs is about a meter, while the denser stands are found in depths of 3-6 dm. The culms are stout, terete, attaining a height of 2.5 m. under

favorable conditions, and rising stiffly above the water or bending in graceful curves. The leaves are reduced to basal sheaths. Seed is usually abundant, while vegetative propagation is secured by perennial, creeping rootstocks.

2. *Scirpus americanus* Pers. (three-square or chair-maker's rush) inhabits the borders of lakes, ponds, and streams, usually in water somewhat shallower than the great bulrush. It does not form thick stands, as does the latter, but is sparingly placed here and there. The culms are sharply three-angled throughout, with concave sides, growing straight upward, sometimes twisted or curved, to a height of a meter. The leaves are basal, narrowly linear, 1-3 dm. long, usually not appearing above the water. The rootstocks are long, stout, perennial.

3. *Pontederia cordata* L. (pickerel-weed) inhabits the shallow water of lakes, ponds, and quiet streams, making its best growth in depths of 2-3 dm. The plants usually stand in clumps, sending up several erect, long-petioled leaves and spikes of showy, blue flowers to a height of 6-12 dm. The leaf blades are ovate to cordate-sagittate, 1-2 dm. long, and about one-half as wide at the base. Stomata occur plentifully on the petioles and both sides of the leaves, but they are somewhat more numerous on the lower than on the upper sides of the blades. Propagation is secured by an abundance of seed, but chiefly by thick, creeping, perennial rootstocks.

4. *Sagittaria latifolia* Willd. (arrow-head) inhabits only the shallowest water and muddy banks of lakes, ponds, and rivers, usually in solitary clumps and seldom covering any considerable area. The leaves are basal, long-petioled, arising from tuberous or fibrous rootstocks to a height of 6 dm. or more. The leaf blades vary greatly in size and shape, but they are nearly always sagittate. Stomata occur sparingly on the upper surface of the blade and on the petiole, but are only moderately abundant beneath.

5. *Acorus Calamus* L. (sweet flag) is rather infrequently found along the margins of streams in water as much as 4-6 dm. in depth. The narrow, sweet-scented, swordlike leaves arise from the thick,

creeping rootstocks to a height of 6 dm. to a meter or more, often forming dense stands over small areas.

6. *Sparganium eurycarpum* Engelm. (bur-reed) inhabits water 4-6 dm. in depth on the borders of ponds, lakes, and rivers, rising to a height of 8-15 dm. The leaves are linear, mostly flat. While propagation is provided vegetatively by perennial, creeping rootstocks, solid stands of any considerable area are exceptional, growth in small groups being usual.

7. *Typha latifolia* L. (common cat-tail) inhabits the marshy banks and shallow water of marshes, lakes, and rivers. The leaves are linear, flat, sheathing at the base, commonly growing to a height of 1-2 m. The plants usually stand in close clumps and sometimes predominate over a considerable area. Stomata are abundant on both sides of the leaves. Propagation is by perennial, creeping rootstocks.

8. *Castalia odorata* (Ait.) Woodville and Wood (sweet-scented water lily) inhabits water of varying depths, covering large areas in shallow ponds and the still water of lakes and slow streams, or mingling freely with open-growing forms of water plants, even occupying the deeper water to the exclusion of other plants when crowded out by competition. The large rootstocks creep through the soft mud, sending up large leaves at the end of long petioles and large, showy, white flowers. The leaves are 0.5-2 dm. wide, orbicular, and float on the surface of the water, frequently partly covering one another in the struggle for space. Stomata occur on the upper side only, but here they are very numerous and their openings are relatively wide. The stomata are kept free from water in the following manner. KERNER (8) states that the leaves are slightly raised where they join the petiole and the margins are somewhat undulating up and down, so that any water which may find itself thereon will roll down from the center of the leaf to the edge on the slightest rocking movement, where it coalesces with the water on which the leaves float. The under side of the leaves is often colored purple by anthocyanin, by virtue of which the temperature of the leaves is said to be raised somewhat above that of the water, tending to increase the transpiration therefrom.

Results

EVAPORATION FROM A FREE WATER SURFACE AND FROM A WATER SURFACE OCCUPIED BY EMERSED WATER PLANTS

A compilation of the data collected during the summers of 1910 and 1911 shows a number of features of interest concerning the evaporation from water surfaces. As would be expected from a consideration of the various plants used, their differences of growth, habit, and structure, together with the varying physical factors, the results show considerable diversity in total and relative amounts of evaporation. A vast amount of data has been recorded throughout the course of the investigation, all of which it is impossible to include in this paper. The statistical tables and graphs which are published here for the most part summarize the more detailed data. The results fall naturally into several groups, which will be taken up successively.

(a) *Total amount of water evaporated*

Tables IV and V give in tabular form the amount of water added to each tank, which represents the amount of water evaporated by water and plant surfaces during any period, for successive intervals. It will be noted that the total amount of water added varies over a considerable range for the different tanks. If the average of the two control tanks be accepted as the amount of evaporation from a free water surface, to which a value of 1 is assigned, then the plants used in 1910 would stand in order of evaporating power thus: pickerel-weed:cat-tail:arrow-head:great bulrush:three-square rush:water lily as 1.98:1.88:1.55:1.19:1.12:0.86. Using the plant combination indicated in table V, the ratio would appear as follows: cat-tail:sweet flag:bur-reed:pickerel-weed:great bulrush:water lily as 3.05:2.36:2.26:2.08:1.20:0.89. The values for water lily (0.86 and 0.89) and for great bulrush (1.19 and 1.20) are nearly the same for the two years. The other values are much higher for 1911, thought to be due in part to the somewhat drier season and more exposed situation and in part to a more luxuriant growth. The evaporation from the water lily tank was in both years much less than that

from the control tanks. This might be expected from the fact that the lily leaves floated on the water, forming a partial cover and reducing the area of water surface exposed to the air. Moreover, lying in a plane only slightly above that of the water surface itself, the lily leaves were constantly bathed by the very humid atmosphere which is commonly present a short distance above the water surface. It is also probable that the amounts assigned to the taller-growing plants are somewhat lower than the actual, since dew collected heavily on the cooler and broader leaf surfaces during foggy nights and, running down the veins and petioles, found its way into the tanks, thus making the observed measurement too small. The water lily was the only plant found to diminish the evaporation from a water surface. All other plants, especially those with a large leaf and petiole surface exposed to the air, increased the evaporation, in one case as much as three times (for example, cat-tail, table V).

(b) *Periodicity of evaporation*

Referring again to tables IV and V of comparative evaporation, it will be noticed that a comparison of successive day and night records for any one tank usually shows a period of high rate of evaporation during the day, followed by a relatively low rate of evaporation during the succeeding night. This phenomenon is most conspicuous in the cat-tail, sweet flag, pickerel-weed, and others exposing a large transpiration surface to the air, and least evident in the rushes and water lily.

The amounts of evaporation from the various tanks given in tables IV and V have been incorporated for the sake of convenience and ready comparison in charts I–XIV, the standard of comparison being the rate of evaporation in cubic centimeters per hour. Charts I and VIII show the rate from the control tanks, and the mean value has been taken to represent the rate of evaporation from a free water surface. These values are plotted in the graphs of charts II–VII and IX–XIV with a heavy broken line. The heavy solid line represents the rate from the tanks containing emerged water plants, that is, the evaporation from the water surface of the tank plus the evaporation from the plant surfaces. The vertical

distance between the horizontal lines representing the evaporation from the free water surface and that from the water surface and plant surface together represents the evaporation due to the plant surfaces alone.

TABLE IV
COMPARATIVE EVAPORATION IN 1910

DATE	APPROX. TIME INTERVAL IN HRS.	CONDITIONS	AMOUNTS OF EVAPORATION FROM THE TANKS (CC. OF WATER ADDED)							
			Arrow-head	Three-square rush	Pickrel-weed	Cat-tail	Water lily	Great bulrush	Control no. 5	Control no. 2
Aug. 10..	6	Day	834	519	1400	1200	470	550	450	400
10..	18	Day and night	1650	1400	1715	1750	1015	1425	1150	1375
11..	12	Day	1750	1250	2400	2250	1215	1250	1300	1100
11..	12	Night	1150	1030	987	1053	750	1090	975	1100
12..	10	Day	1600	975	2585	2650	900	1080	1140	750
12..	14	Night	1500	1575	1300	1250	990	1550	1225	1570
13..	11	Day	1770	975	2490	2385	975	1150	790	660
13..	13	Night	988	940	1000	1193	630	1000	910	1120
14..	10	Day	1730	995	2425	2445	905	1090	835	762
14..	14	Night	745	750	887	820	475	730	715	767
15..	8	Day	1145	500	1845	1840	575	673	500	407
16..	9	Day	940	553	1247	1245	450	610	452	425
16..	14	Night	650	553	654	650	420	600	500	500
17..	10	Day	1495	815	2060	1785	630	863	580	678
19..	11	Day	2070	1317	2890	2673	1185	1550	1340	1130
19..	13	Night	1305	1300	1398	1358	863	1327	1228	1250
20..	11	Day	2058	1235	2670	2505	970	1405	1000	1063
20..	23	Night and day	2950	2150	3728	3378	1435	2063	1837	1913
21..	12	Night	783	685	890	900	395	785	655	595
26..	25	Day and night	2920	2075	3470	3255	1675	2175	1725	1918
27..	7	Day	1042	575	1590	1500	555	805	543	460
27..	13	Night	955	950	925	865	590	850	860	990
28..	25	Day and night	2755	2070	3660	3375	1587	2180	2100	1395
29..	10	Day	2267	1443	3040	2587	810	1550	958	1040
29..	13	Night	1080	975	1305	1235	650	1055	1045	905
Totals for an approximate period of 324 hours (cc. of water added).....			38,132	27,605	48,561	46,207	21,115	29,406	24,813	24,273

In most instances the evaporation during the night was found to be in excess of that from the free water surface, indicating that emerged water plants transpire during the night. An exception is the case of the water lily, in which the evaporation was usually

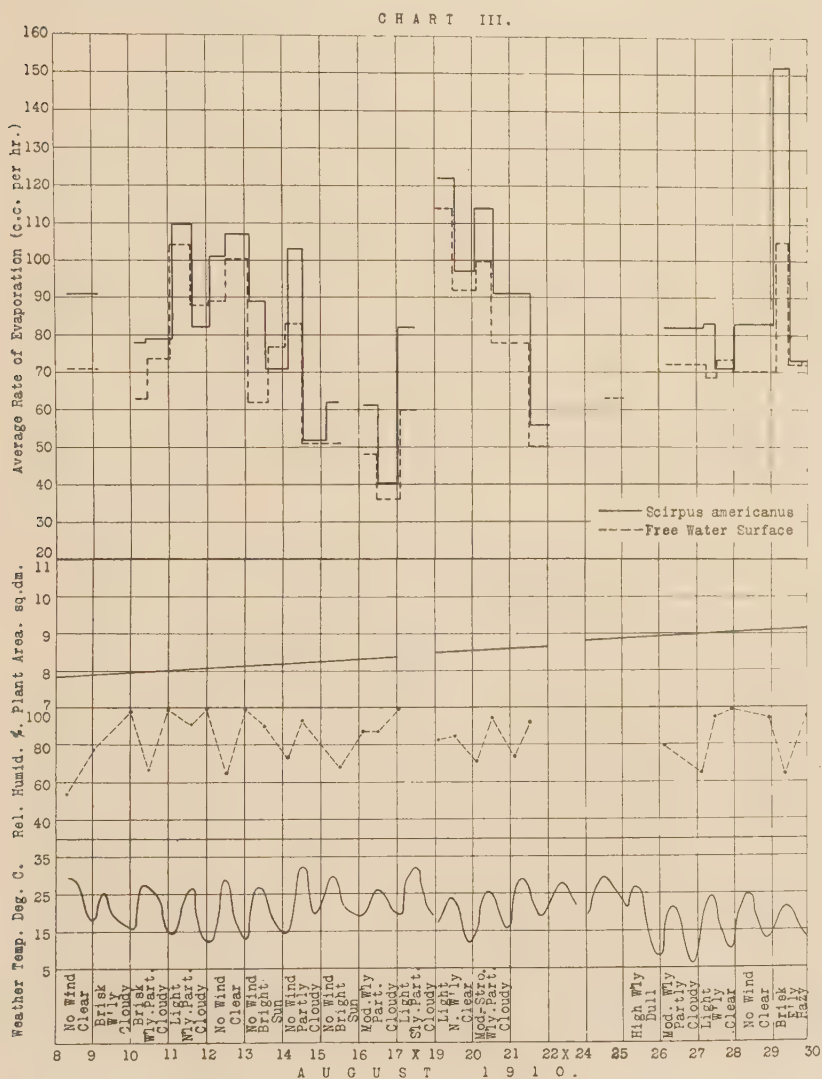
less than from the free water surface. We are led, then, to the conclusion that transpiration from these plant surfaces occurs both by day and by night, but that the day transpiration is greatly in excess of that taking place at night. These observations are

TABLE V
COMPARATIVE EVAPORATION IN 1911

DATE	APPROX. TIME INTERVAL IN HRS.	CONDITIONS	AMOUNTS OF EVAPORATION FROM THE TANKS (CC. OF WATER ADDED)							
			Cat-tail	Sweet flag	Pickrel-weed	Bur-reed	Great bullrush	Water lily	Control no. 8	Control no. 1
Aug. 30..	12	Day	4160	3590	2860	3085	1630	1175	1095	1420
30..	12	Night	1000	780	680	1145	680	620	600	615
31..	12	Day	3050	2405	1905	2100	745	490	585	510
31..	12	Night	600	540	560	520	595	520	575	575
Sept. 1..	11	Day	5110	3410	3200	3360	1300	790	950	835
1..	13	Night	925	860	870	800	660	455	575	655
2..	24	Day and night	7560	5730	5075	5725	3120	2310	2780	2880
3..	12	Day	4850	4300	3090	3945	1960	1415	1545	1690
3..	12	Night	1050	935	920	975	1030	830	830	1030
4..	11	Day	5680	4200	4060	3540	1880	1345	1270	1550
4..	12	Night	780	730	640	725	710	630	655	720
8..	8	Day	1885	1495	1885	1250	400	265	255	265
8..	14	Night	440	375	340	380	240	210	225	250
9..	10	Day	3240	2285	1915	2250	580	350	360	350
9..	13	Night	640	580	400	530	510	465	510	600
10..	9	Day	3030	2025	1735	1940	535	300	365	345
10..	15	Night	550	460	210	440	270	175	220	240
13..	11	Day	4640	3620	2800	3450	1700	1130	1180	1390
13..	13	Night	1430	1240	1220	1280	1195	1030	1050	1180
15..	8	Day	3880	2275	2425	2570	700	485	530	440
15..	13	Night	700	655	575	740	510	430	380	470
19..	13	Night	1500	1360	1285	1250	1350	1120	1200	1330
Totals for an approximate period of 270 hours (cc. of water added).....			56,700	43,850	38,650	42,000	22,300	16,540	17,735	19,340

in accordance with the results obtained by CLAPP (3) and others with land plants, in which it has been found that land plants transpire principally during the day and only feebly if at all at night.

casioned by the removal of the various parts from time to time. This was thought to approximate very nearly growth under normal



conditions of development. Both sides of the leaf blades, with the exception of those of the water lily, which contain stomata on the upper side only, and those portions of the petioles or culms above

the level of the water surface were taken as a basis for transpiring surface, since these surfaces all contained stomata in greater or lesser numbers. The unit of surface selected was, for convenience, the square decimeter.

Table VI shows the rate of transpiration in cc. per hour per sq. dm. of total plant surface. Several things are brought out. The rate during the day is usually much higher than the night rate. This is not so apparent in the case of the water lily, for in this instance the difference between day and night rates is not so great as in the other cases. This is remarkable when it is considered that the lily leaves float on the surface of the water in a very humid atmosphere, especially at night, whereas the taller-growing plants are in a relatively less humid layer of air. This may be accounted for in part by the fact that the lily leaves, because of their contact with the water, are warmer at night than those leaves which project into the air, which is much cooler than the water during most of the nights.

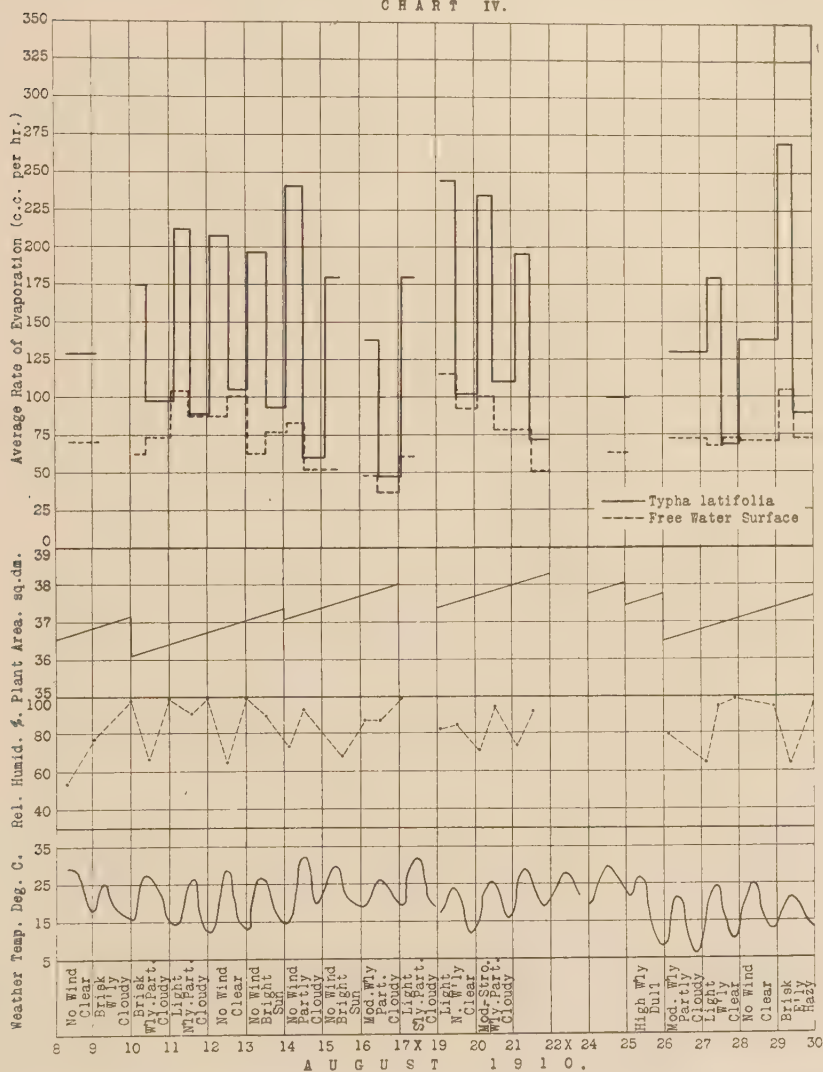
TABLE VI
RATE OF TRANSPIRATION PER AREA OF SURFACE

DATE 1910	CONDITIONS	TRANSPIRATION IN CC. PER HOUR PER SQ. DM. OF TOTAL PLANT SURFACE						
		Pickereel-weed	Cat-tail	Arrow-head	Great bulrush	Three-square rush	Water lily	Free water
Aug. 10..	Day	1.758	1.565	0.718	2.463	2.007	1.704	1.359
10..	Day and night	0.274	0.332	0.224	0.616	0.627	1.184	1.623
11..	Day	1.654	1.483	0.501	2.439	0.750	2.280	2.281
11..	Night		0.000	0.044	0.366		1.125	1.929
12..	Day	1.603	1.608	0.827	1.325	1.481	1.799	1.952
12..	Night	0.060	0.054	0.056	2.409	0.864	1.428	2.193
13..	Day	1.696	1.797	1.045	3.690	3.198	2.017	1.381
13..	Night	0.012	0.216		0.357		0.811	1.688
14..	Day	1.812	2.129	1.050	2.927	2.439	2.119	1.820
14..	Night	0.140	0.108	0.011	0.244	0.122	0.579	1.118
15..	Day	1.665	1.885	0.920	2.409	1.333	1.647	1.118
16..	Day	0.872	1.194	0.613	1.789	1.566	1.083	1.053
16..	Night	0.172	0.146	0.120	0.954	0.482	0.605	0.780
17..	Day	1.670	1.566	0.982	3.187	2.631	1.407	1.316

Aside from these differences between day and night rates of transpiration, there is also a great difference between the rates from different species during the same time period. Again, the

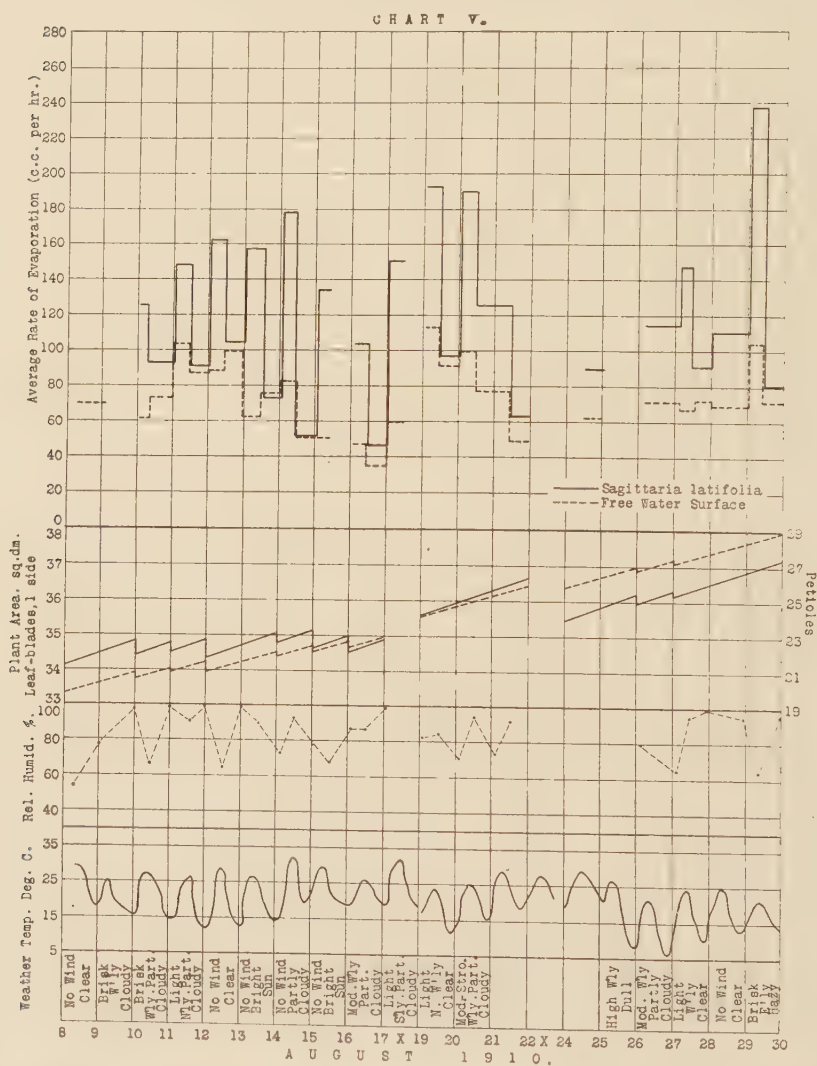
difference is not so marked in the case of the night readings, but is conspicuous during the day. On a basis of surface exposed, the

CHART IV.



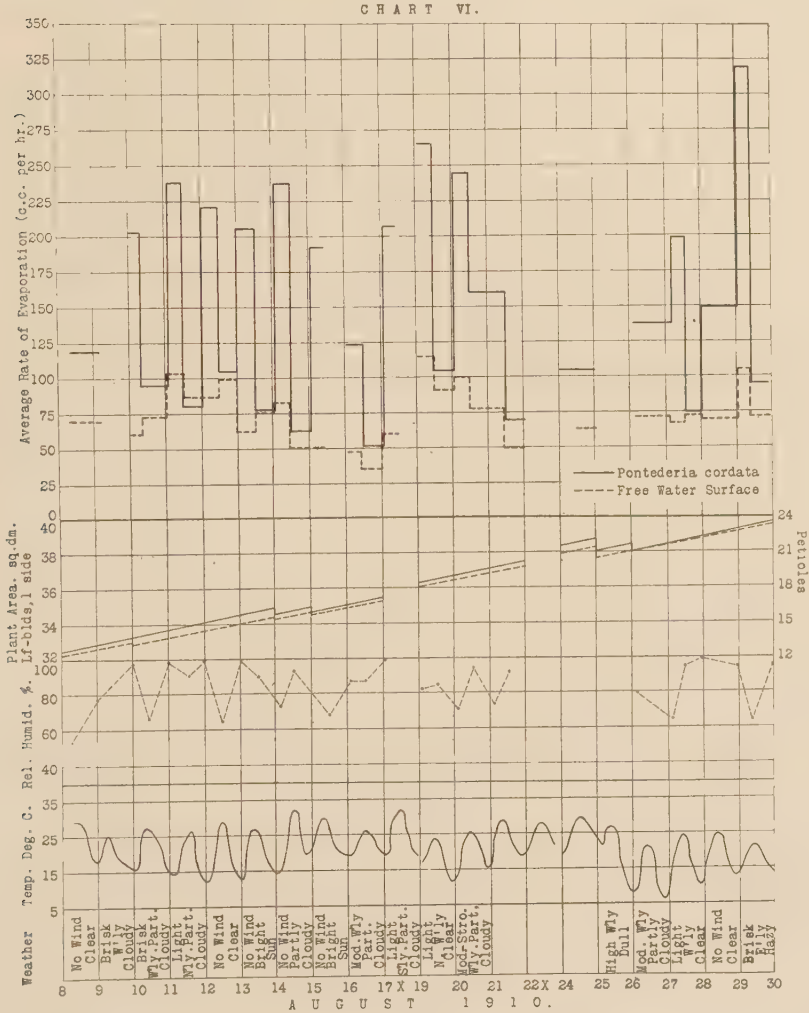
arrow-head would seem to be the least effective from the standpoint of water dispersal, the rushes and water lily showing greatest efficiency, with the pickerel-weed and cat-tail occupying an inter-

mediate position. GATES (7), with a temperature of 26° C. and a relative humidity of 69 per cent, reports that cuttings of *Sagittaria*



latifolia had a rate of water conductivity of 49 cm. per hour, while cuttings of *Typha latifolia* had a rate of 114 cm. per hour. It should be remembered, too, that in the case of the cat-tail all of the

stomatal surface is not equally effective, owing to the sheathing habit and consequent crowding of the leaves, while in the pickerel-weed and arrow-head a similar decrease in transpiration is caused



by shading and by hindrance to air movements by the closely growing leaves and petioles. This might explain in a measure, or at least have some influence on, the differences in transpiration rates for different species.

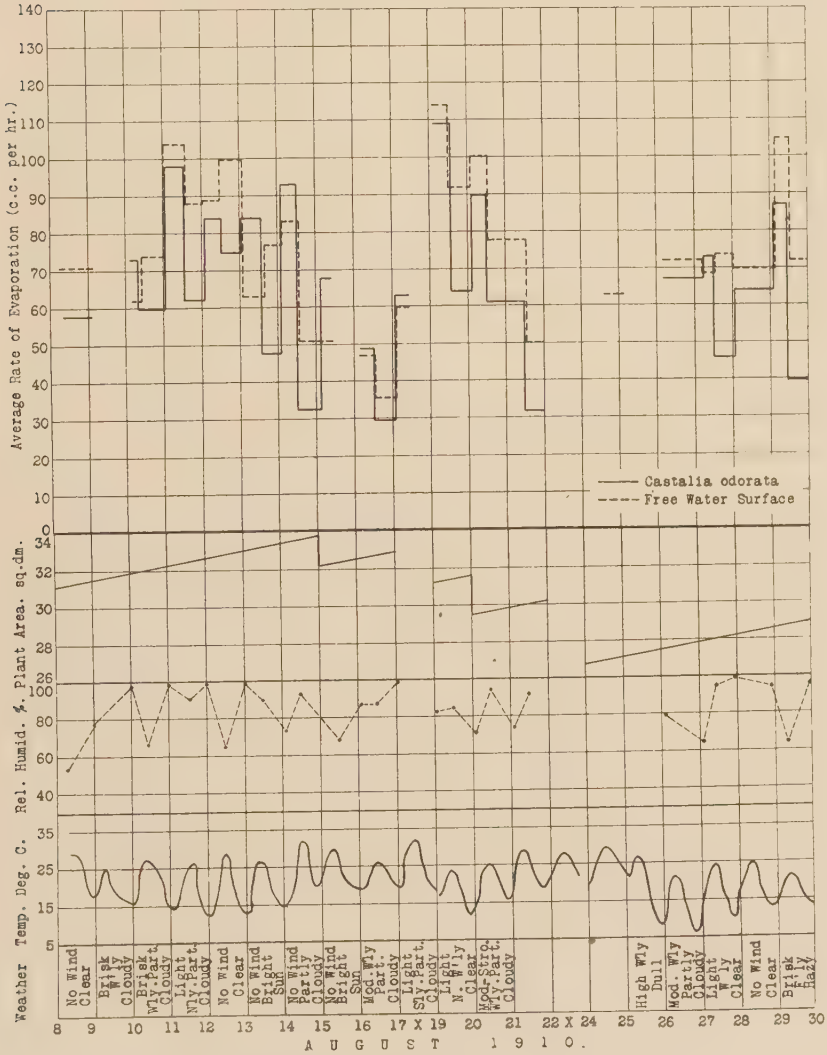
(d) *Comparative evaporation from a plant surface and from a free water surface*

Table VI, referred to above, is interesting from the standpoint of a comparison of equivalent areas of plant surface and the surface of free water. It has been commonly held that the transpiring surface of a land plant is normally unable to evaporate as great a quantity of water as is evaporated from a free water surface of the same area and exposed to the same external conditions. GATES (7), experimenting with potted bog plants, makes the statement that three to five times as much water is evaporated from a free water surface as is evaporated from an equivalent area of leaf surface during a hot summer day. This would seem reasonable in view of the fact that the stomatal openings, being widely scattered and not continuous, even when very numerous, do not even approximate the amount of space above a water surface. It should be remembered in this connection, however, that the tissues of water plants are in general very thin, as is evidenced by their early collapse on removing them from the water, and the epidermis shows little or no cuticularization. It is probable, then, that the amount of cuticular transpiration from water plants is greater than is popularly supposed, and that it may compensate to a greater or lesser extent the insufficiency of stomatal openings. In view of these facts the data of table VI show rather interesting results.

Leaving out the case of the arrow-head for the present, it will be seen that in a majority of the day readings the rate of evaporation from the plant surfaces nearly equals the rate from the free water surface, and in some cases even exceeds this rate. Thus, on August 10, 13, 15, and 17, all of the day rates from the plant surfaces exceeded that from the free water surface; on August 14 and 16 all but one showed a greater rate, pickerel-weed in both instances being deficient; but on August 11 there was only one, and on August 12 there were no plant surfaces with a rate greater than that from free water. The transpiration rates at night from the plant surfaces are low compared with those from the free water surface. The one exception is the water lily, whose transpiration rate at night was relatively high compared with that of the other plants, although in no case recorded did it equal that from the

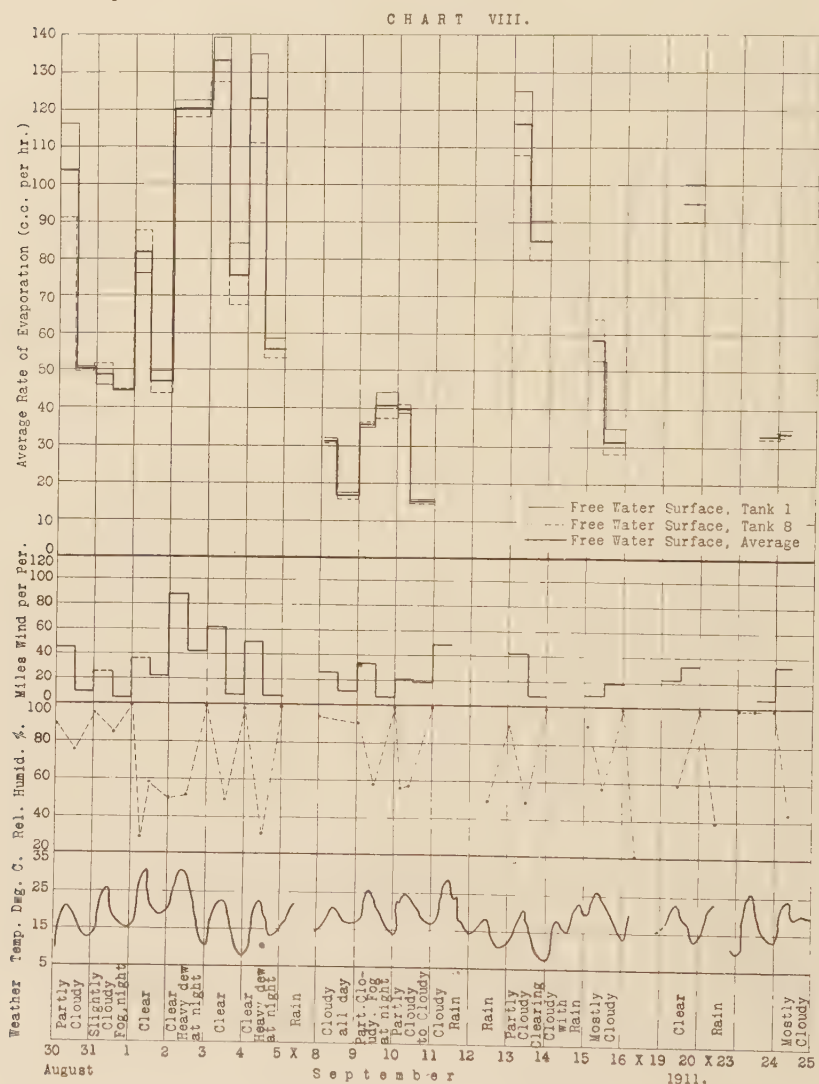
free water surface. Just what is the cause of these variations is not clear, since a survey of the weather conditions for these days gives

CHART VII.



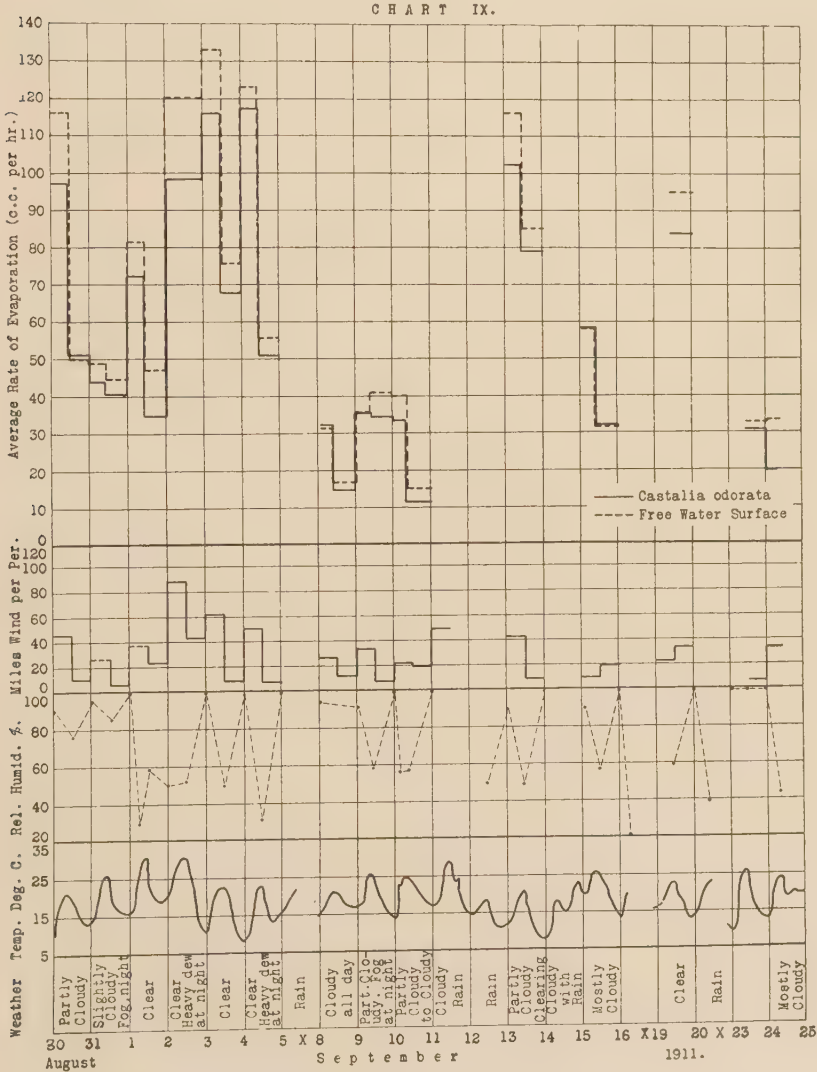
no indication of the controlling factors. The fact, however, that the majority of the day rates is greater than that from free water, while all of the night rates are less, leads to the supposition that

the factor, or combination of factors, responsible for the difference acts differently or with different intensities at night than during the day.



Among the plants used the water lily offers perhaps the fairest comparison, since the floating leaves are but slightly elevated above the water surface and physical conditions are thus nearly equal for

leaf and water surfaces. It is said (8) that the purple coloring matter of the lower side of the lily leaves absorbs the sun's rays and in this way tends to increase the internal temperature of the leaves



and hence the transpiration. Experimental evidence seems to be lacking on this point, and it is the belief of the writer that, assuming any slight changes in temperature to be probable, they would be

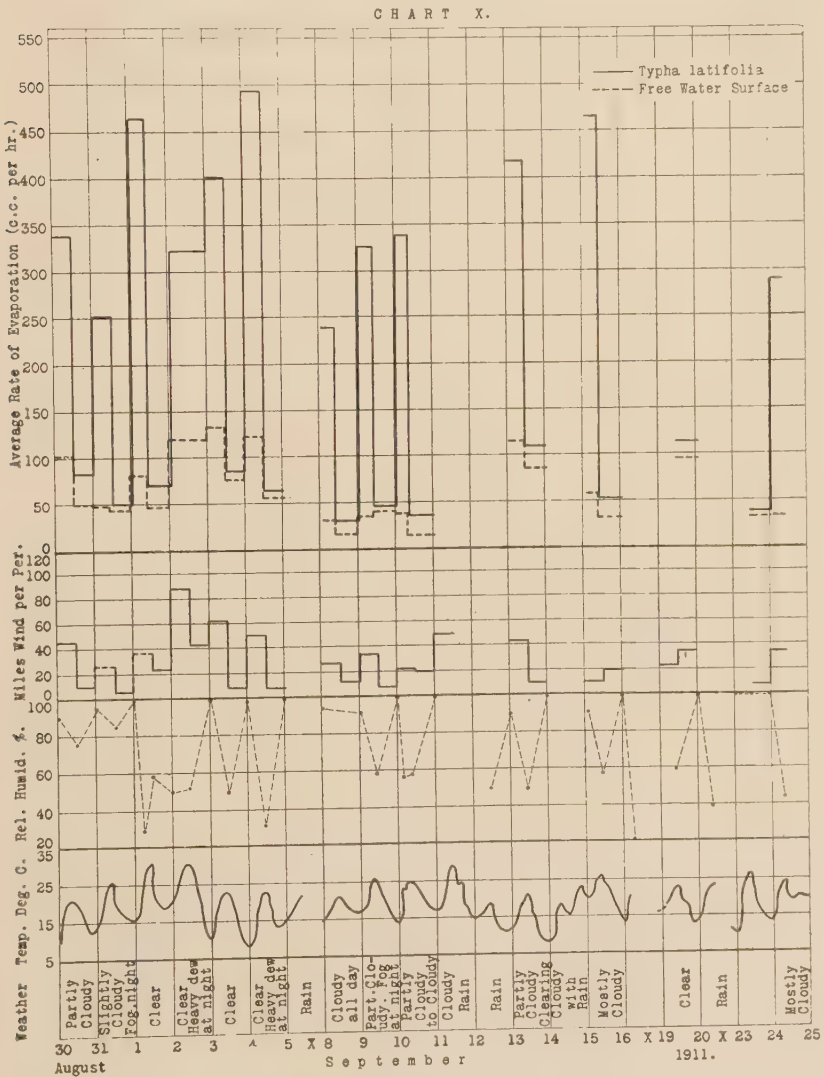
counteracted or even destroyed by convection currents in the water surrounding the leaf. It is not thought, then, that the increase in transpiration in the water lily is due to temperature differences, but to other causes. The arrow-head is a transition plant, growing, with some modifications, on land, as well as in water, and it is interesting to note that this plant, even when growing in a hydrophytic habitat, behaves more like a typical land plant in the matter of its transpiration.

(e) *Relation of certain physical factors to transpiration*

An inquiry into the various external factors which exert an influence on transpiration leads to some interesting conclusions. It is not our purpose to consider all of the possible factors which may or may not affect transpiration, nor to consider every factor separately, but rather to consider the combined effect of the more important factors as they occur under natural conditions in the field. Relative humidity, temperature, and wind are quite generally recognized as the principal factors affecting evaporation from an open water surface. In so far as plant transpiration is largely a physical process, omitting, therefore, the phenomena of root pressure, increased protoplasmic activity, and other purely physiological mechanisms, it would be expected that these three factors would be of principal importance in plant transpiration.

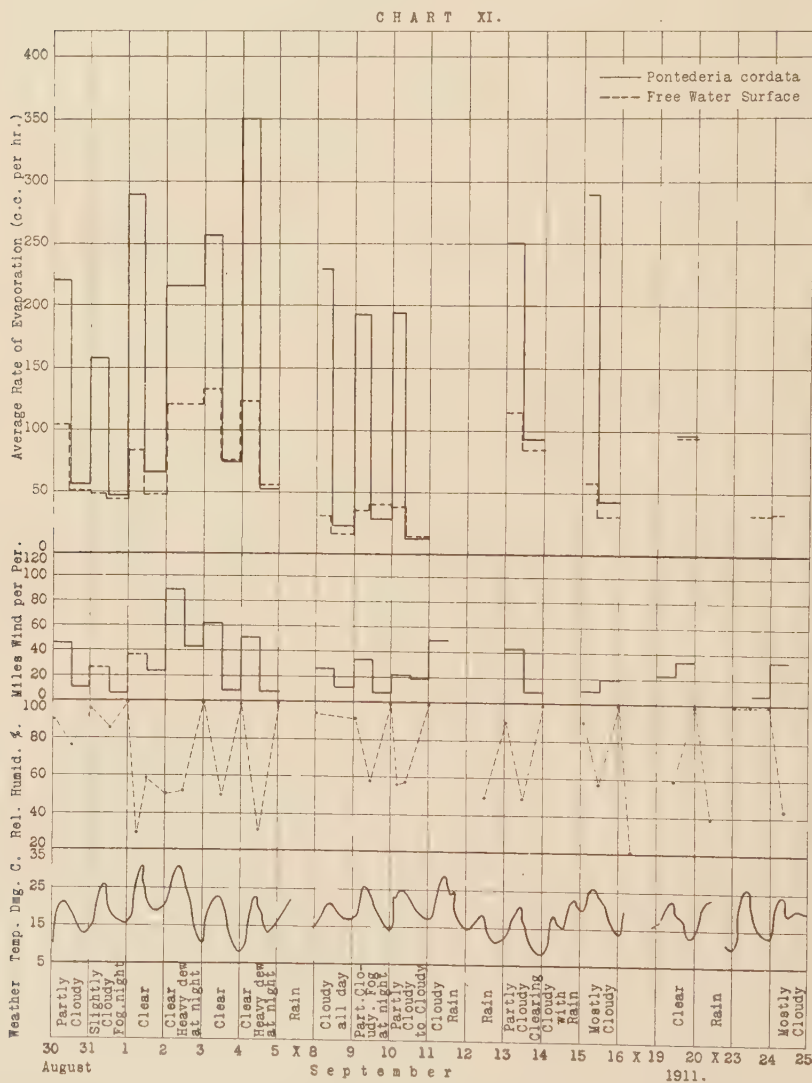
1. TEMPERATURE.—The graphs of transpiration shown in charts VIII–XIV show the effect of temperature on the rate of transpiration. With few exceptions the temperature during the night was much less than that during the day. The transpiration graphs show this same relationship as between night and day, the rate during the day being high and correspondingly low during the night. That temperature is not the only factor is shown by the fact that the highest rate of transpiration recorded for most of the plants occurred during the day of September 4, at which time the day temperature was somewhat low. Likewise, during the periods of highest day temperature, that is, September 1, 2, and 15, the transpiration was only moderate. Moreover, on the nights of August 31 and September 3 and 4 the wind velocity was very nearly constant, from 3–5 miles for the period, and the percentage

of relative humidity was about the same. The temperatures on the nights of August 31 and September 4 were nearly equal, and for most of the plants the rates of evaporation were correspondingly



similar. On the night of September 3, however, the temperature was much lower than in the other two cases, but the rate of evaporation was higher.

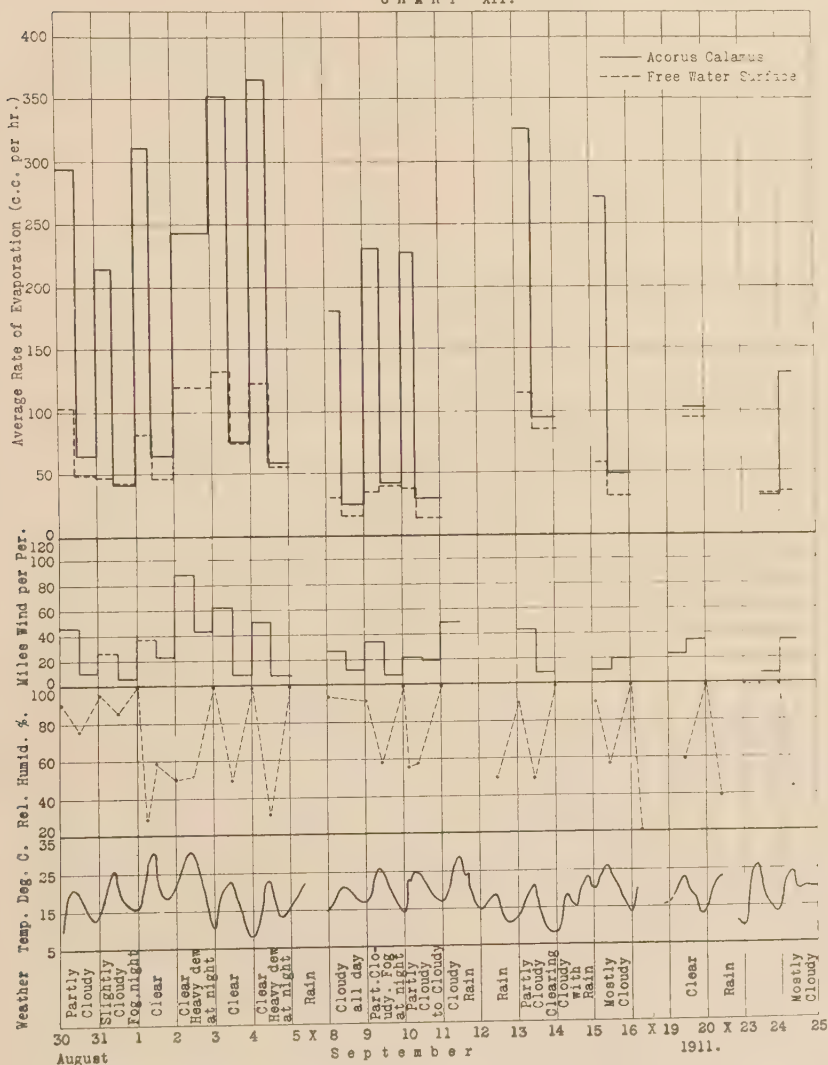
2. RELATIVE HUMIDITY.—The records of relative humidity are more or less incomplete, owing to the lack of readings during the



day; and it is probable that the day humidity was often less than indicated, although it is thought that these readings are relative. However, it was generally true that the humidity was very high

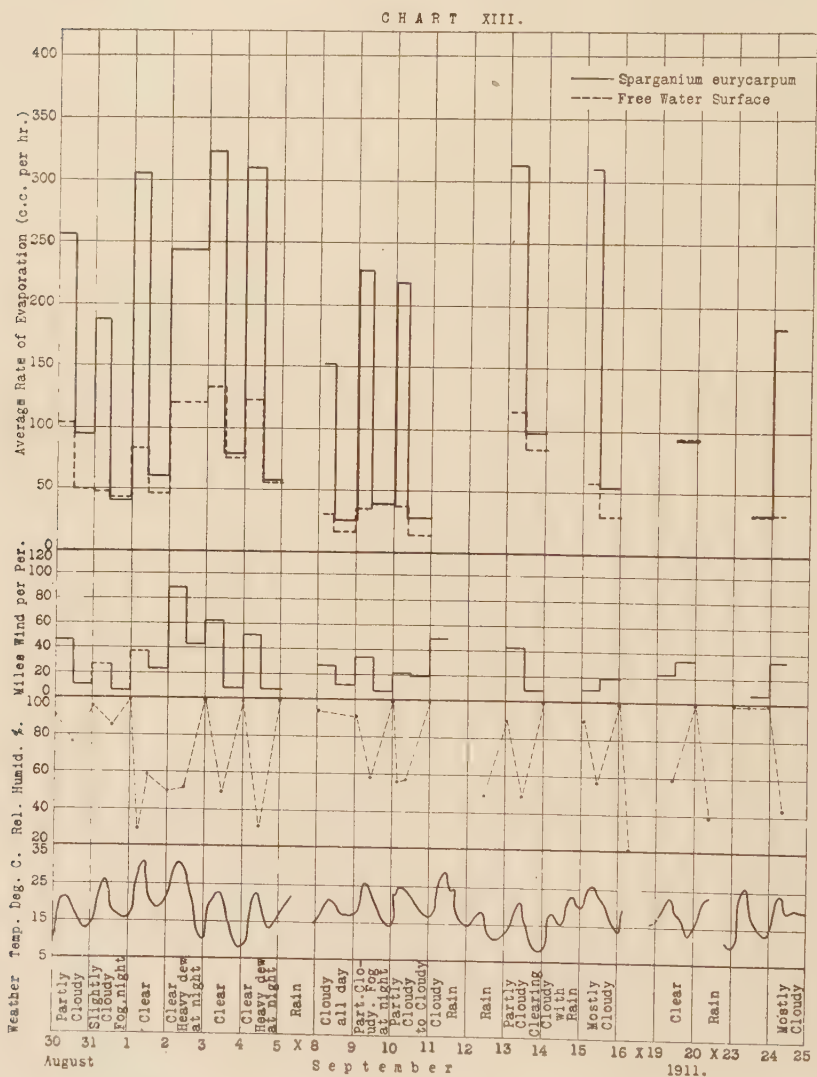
during the night, almost reaching the point of saturation in several instances. Probably this extreme limit was reached in most cases

CHART XII.



between 4 and 6 o'clock in the morning, when the temperature was at its lowest point. Referring again to charts VIII-XIV, it will be observed that periods of high humidity are accompanied by a low

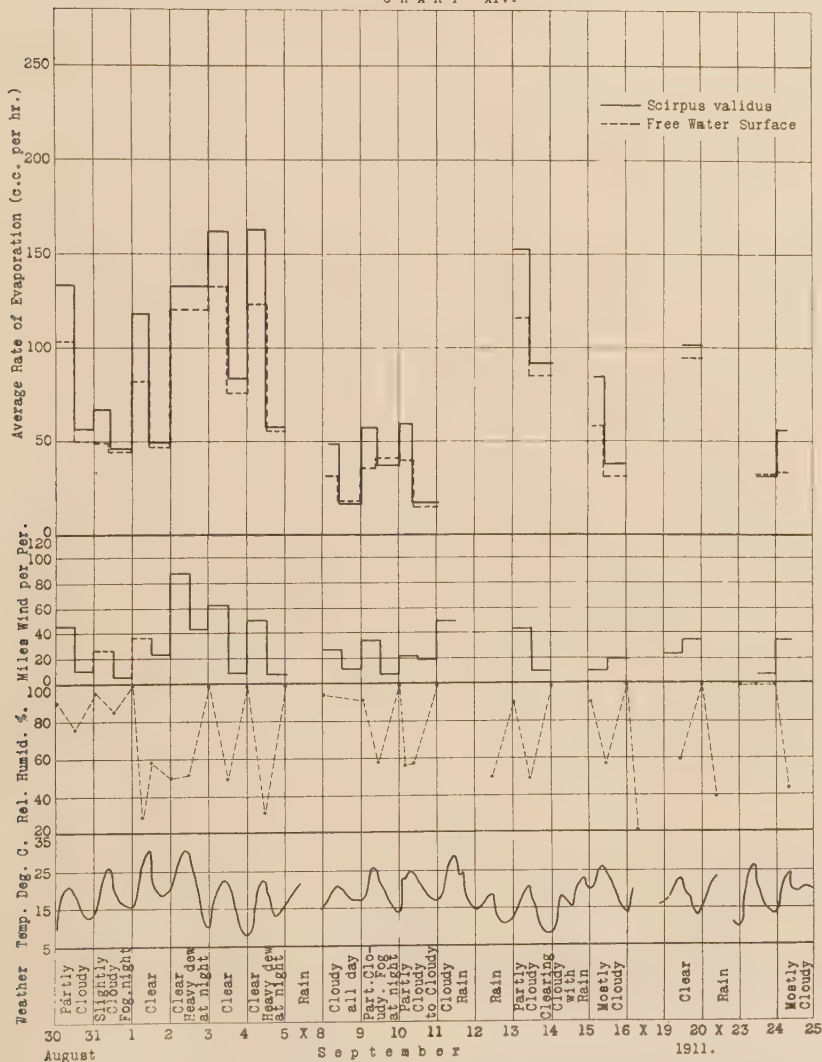
transpiration rate. Also interesting are the results for September 10, when the wind velocity was practically uniform for day and



night, and temperature varied through a small range; transpiration was high while humidity was low, with a reversal of positions when the humidity became high.

3. WIND is undoubtedly an important factor in plant transpiration, at least up to a certain point, that is, to a point at which the

CHART XIV.



wind is strong enough to carry away the moisture as fast as it forms on the surfaces of the plants. It is doubtful, however, if transpiration is materially increased with winds in excess of this amount.

The effect of wind was shown clearly on September 8 (charts VIII–XIV), where relative humidity and temperature did not vary much, but the miles of wind were greater during the day than during the night; the rate of transpiration was greater during the period of greater wind. That wind is a minor factor is shown by the fact that the periods of highest wind velocity are not in all cases periods of highest transpiration rates.

Whether transpiration from plant surfaces is due to one factor more than to another, we are not prepared to say from an examination of the data at hand. Indeed, considering the intimate relation existing between temperature and humidity, it would be impossible to determine the exact influence of the one without being able to maintain the other constant, a state of rare occurrence in nature. And, after all, we are not greatly concerned with these various factors individually, since not one of them of itself is capable of exerting its greatest influence without the accompanying influence of the others. Whether the factors which influence plant transpiration are identical with those which influence evaporation from water surfaces, it is clearly brought out in these experiments that the effects produced on the one and the effects produced on the other are profoundly different in their intensities, and we are led in consequence to the opinion that plant transpiration is not a strictly physical process, but a physiological process as well. The data for 1910 contained in charts I–VII, while not mentioned in detail here, confirm the same conclusions.

Summary

1. Emerged water plants transpire large amounts of water.
2. With one exception (water lily), the evaporation taking place from a water surface occupied by emerged water plants is much greater than that which takes place from a free water surface of the same area and subjected to the same external conditions.
3. The amount of evaporation from a water surface on which water lilies are growing is less than that which takes place from a free water surface of the same area and subjected to the same external conditions.

4. The amount of evaporation from a water surface occupied by emerged water plants depends upon the following factors: (a) the species of plant; (b) the density of plant stand; (c) the amount of plant surface exposed to the evaporating power of the air; (d) the height of the plant growth above the level of the water; (e) external factors (physical factors, like wind, temperature, relative humidity, etc.); (f) internal factors (chemical and physiological phenomena within the plant).

5. Transpiration from emerged water plant surfaces occurs both by day and by night, but transpiration by day is greatly in excess of that by night.

6. For different species there is no constant ratio between rate of transpiration and the area of surface exposed.

7. The rate of evaporation from the transpiring surface of an emerged water plant during the day may equal, and in some cases may exceed, that from a free water surface of the same area; but at night the evaporation from a free water surface is usually greatly in excess of that from a transpiring plant surface.

8. Wind, temperature, and relative humidity undoubtedly have a great influence on the rate of transpiration of emerged water plants, but these factors alone do not explain the great difference existing between transpiration of emerged water plants and the evaporation from a free water surface.

9. These data are of economic importance in indicating what plants should be grown in and what plants should be excluded from storage reservoirs in regions of small rainfall and scant water supply.

In conclusion I desire to extend my hearty thanks to Professor F. C. NEWCOMBE, who has directed this work throughout and who has been a constant inspiration and help, and to Mr. GARDNER S. WILLIAMS and the Eastern Michigan Edison Company for their aid in furnishing the tanks and pontoons and for their suggestions on methods of construction.

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